REFERENCE 35

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CF-61-4-33

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SUBJECT: Neutron Multiplication Experiments with Enriched Uranium Metal in Slab Geometry

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FROM: J. T. Mihalczo and J. J. Lynn

ABSTRACT

Critical thickness of uranium metal slabs enriched to 93.15% in the U^{235} isotope have been obtained by a technique involving source-neutron multiplication counting. Subcritical assemblies of metal slabs were constructed to within, in most cases, 95% of critical mass, and the resulting reciprocal multiplication curves extrapolated to critical thicknesses. Slab dimensions ranged from 5 x 5 in. to 25 x 25 in., and thicknesses of infinite slabs have been extrapolated from the data. Plexiglas, in thicknesses from 0 to 6 in., beryllium, and AGOT graphite served as neutron reflectors. Previous work with uranium-Plexiglas lattices has been extended to lattice densities of 0.33 and 0.50, the latter being the limiting density under the conditions of the experiment.

ERRATA: ORNL-CF-61-4-33

Page 6: Table 1, Column 3, "Percent of Critical Thickness Assembled" for a 25 x 25 in. slab with 6 in. reflector should read 83 rather than 94.

Last Column, "Effective Extrapolation Distance" for infinite slab with no reflector should be 2.25 rather than 2.75 cm.

Page 9: First paragraph, last sentence should read "It is also evident that, for reflected systems, the extrapolation distance becomes a strong function of the relative dimensions of the slab as the height-to-area ratio decreases."

Page 10: Figure 5, the intercept of the unreflected curve should be 2.25 cm rather than 2.75 cm.

Page 16: Table A-2, First and Last Columns "Uranium Thickness" 4th entry from bottom, for a 25 x 25 in. slab with 6 in. reflector the uranium thickness is 0.59 in. rather than 0.62 in.

Page 24: Figure A-6, for the 25 x 25 in. slab with 6-in. reflector the point at 0.625 in. should be plotted at 0.59 in.

INTRODUCTION

The determination of critical dimensions of both individual units and arrays of units of fissionable material, in simple shapes and with minimal interference from supports, etc., has been a continuing program at Oak Ridge National Laboratory. In the experiments presently reported, uranium metal slabs, enriched to 93.15% in U^{235} and ranging in area from 5 x 5 in. to 25 x 25 in. were assembled, and although not made critical produced sufficient source neutron multiplication to allow quite precise estimation of the critical thickness. Neutron reflection was accomplished with Plexiglas, in thicknesses from 0 to 6 in. Also included are preliminary results from graphite- and beryllium-reflected experiments, not yet concluded.

The results of these experiments provide guidance in the development of methods of reactor analysis and confirmation of analytic predictions, and are valuable in establishing safety limits for production and fabrication procedures. Of particular interest is the thickness of a critical slab having an effectively infinite area. The work is closely related to that at Los Alamos Scientific Laboratory with critical cylinders of 93.4% U^{235}-enriched uranium metal as large as 15 in. in diameter.[1]

Measurements with arrays of 1-in.-thick, 8- x 10-in. slabs of uranium, separated and reflected with 1-in.-thick Plexiglas, have been reported previously.[2] Lattice densities (the ratio of fissile unit volume to unit cell volume) ranged in these experiments from 0.024 to 0.06. Extension of these data to lattice densities of from 0.33 to 0.50 is reported below.

EQUIPMENT AND MATERIALS

Slab arrays were assembled on the existing "split-table" apparatus, modified by mounting a smaller aluminum table on one half of the table, as shown in Fig. 1. The smaller table was movable a distance of 2 in. with respect to its support, being magnetically held in operating position against a compressed spring capable, on release, of propelling the table through its first inch of travel in 60 msec. Assemblies were constructed in two parts, each on a half of the split table. The rapid separability of the assembly, made possible by the combined motions of the two movable tables, constituted the principal safety feature of the experiments.

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1. G. E. Hansen, H. C. Paxton, and D. P. Wood, Nuclear Sci. and Engr. 8, 570 (1960).
2. J. T. Mihalczo and J. J. Lynn, Multiplication Measurements with Highly Enriched Uranium Metal Slabs, ORNL-CF-59-7-87 (July 27, 1959).

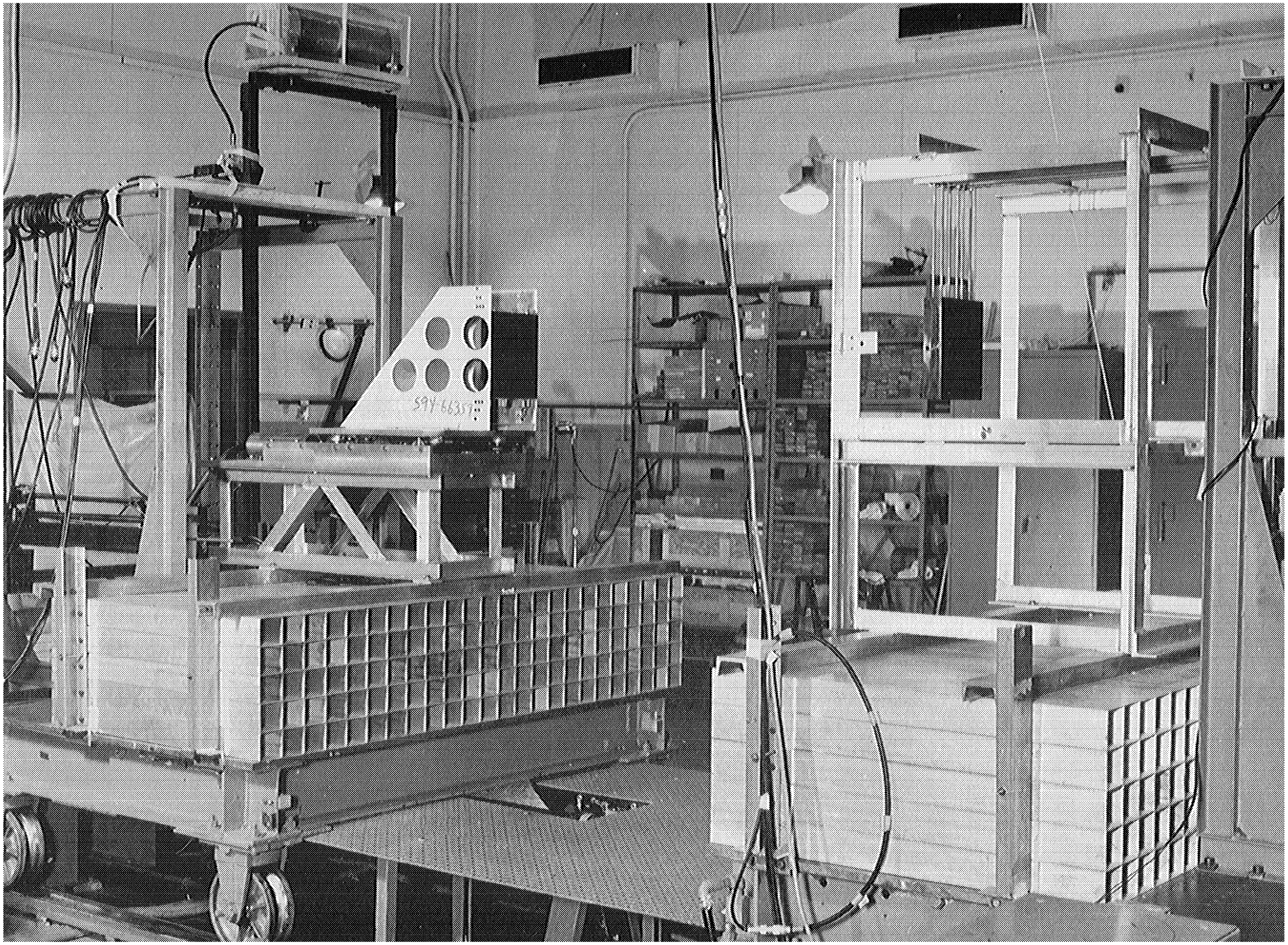

Fig. 1. Experimental Arrangement.

The aluminum support structure for the uranium was made as light as possible in order to minimize back-scattering of neutrons. For some of the 8- x 10-in.-slab assemblies, in fact, the uranium on the fixed portion of the split table was suspended by aluminum rods, as shown in Fig. 2. Although neutron reflection was indeed reduced, this arrangement lacked sturdiness and tended to introduce uncertainties in results by permitting cracks and voids to remain upon table closure. In all assemblies the number of individual pieces was held to a minimum to reduce the void content.

The uranium slabs available for these experiments are described in Table A-1 (Appendix A). The U^{235} enrichment of the metal was 93.15 wt%; the density was 18.7 g/cm^3. Density of the Plexiglas (methyl methacylate) used as a neutron reflector, was 1.2 g/cm^3. Beryllium, density 1.86 g/cm^3, and AGOT graphite, density 1.72 g/cm^3, were also used as reflectors.

A Po-Be source, of $\sim 10^7$ neutrons/sec, and three BF_3 gas-filled counters, located about the array, were used to measure the neutron multiplication. The source was usually inserted in a 3/8-in.-dia hole centered in a 5- x 8- x 7/8 in. slab of metal. With thinner assemblies the source was placed adjacent to the uranium.

EXPERIMENTAL RESULTS

Reflected and Unreflected Uranium Slab Assemblies

Critical thicknesses under several conditions of neutron reflection have been determined for slabs ranging in dimension from 5 x 5 in. to 20 x 20 in. by source-neutron multiplication measurements. Typically, neutron multiplication as a function of slab thickness was measured to a limit, in most cases, of more than 95% of the critical thickness, and the resulting reciprocal multiplication curve extrapolated to critical thickness. The values, together with results from larger slabs with a single reflector condition, are given in Table 1 and Fig. 3.

The thickness of a critical slab infinite in extent was obtained from a plot of critical thickness vs. inverse area, by extrapolation to an inverse area of zero. The results of a linear extrapolation of data for slabs of 100-in.^{2} area and larger, made in Fig. 4, are 0.60 ± 0.03 in., the critical thickness of a slab reflected by 6 in. of Plexiglas, and 2.50 ± 0.15 in., the thickness of a similar but unreflected slab. The latter value and its uncertainty include the (estimated) effect of reflected neutrons.

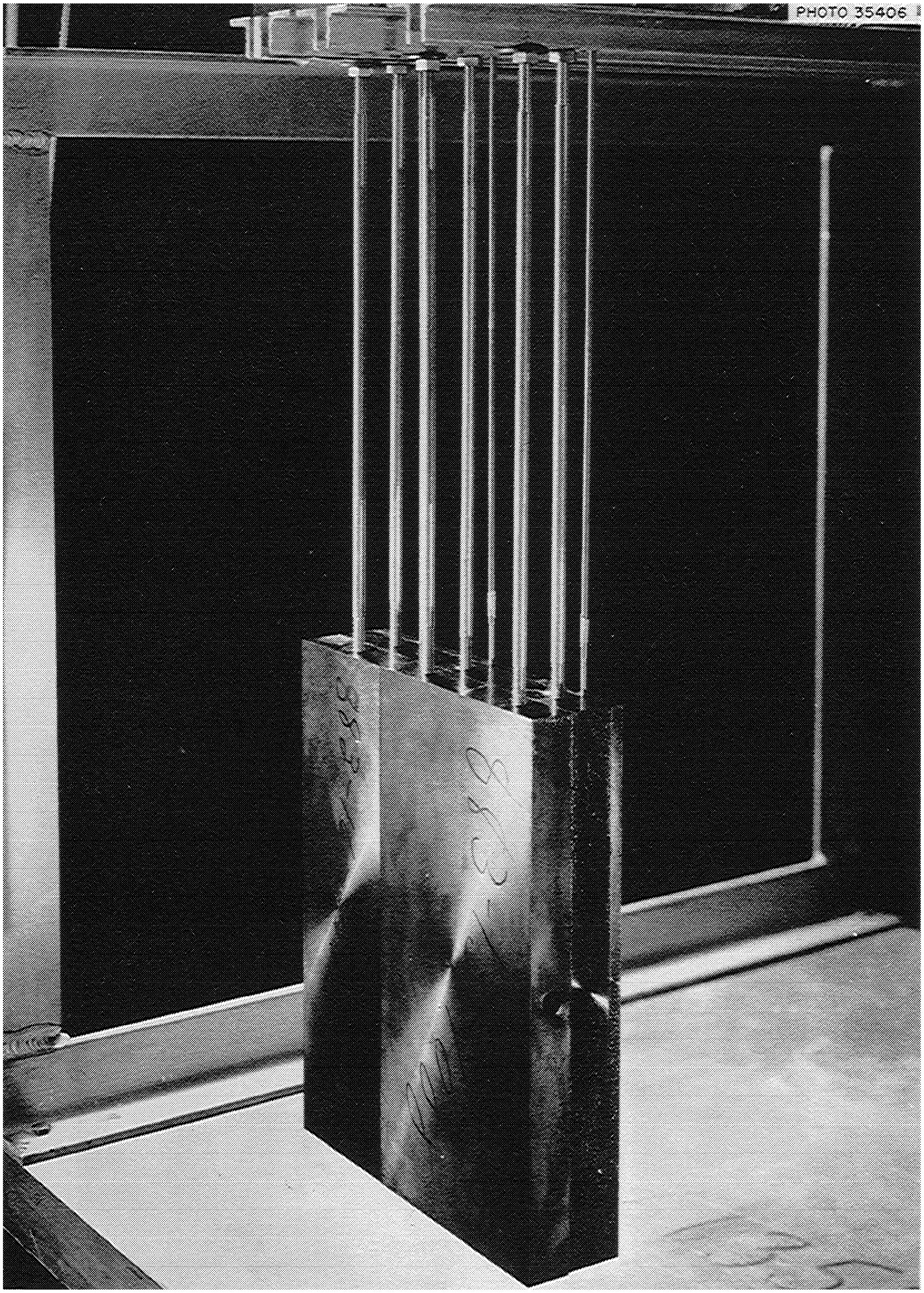

Fig. 2. Support for Unreflected Uranium Slabs.

Table 1. Critical Thickness and Critical Mass of Slabs of 93.15%-U^{235}-Enriched Uranium Reflected with Plexiglas of Various Thicknesses

Plexiglas Reflector Thickness (in.)	Critical Thickness,[a] t, (in.)	Per Cent of Critical Thickness Assembled	$\frac{t}{\sqrt{Area}}$	Critical Mass (kg of U^{235})	Effective Extrapolation Distance, λ_c (cm)[b]
		5- x 5-in. Slab			
0	9.13	97	1.826	65.6	2.04
1	4.96	96	0.992	35.5	3.09
2	3.70	98	0.740	26.5	3.73
6	3.05	98	0.610	21.8	4.14
		8- x 10-in. Slab			
0	3.74	97	0.42	85.7	1.95
1	2.64	95	0.30	60.5	3.09
2	1.89	93	0.21	43.3	3.91
3	1.63	92	0.18	37.4	4.21
4	1.55	97	0.17	35.5	4.29
6	1.53	98	0.17	35.0	4.32
		10- x 10-in. Slab			
0	3.32	98	0.332	95.1	2.15
1	2.32	97	0.232	65.6	3.27
2	1.72	93	0.172	49.3	3.95
6	1.30	96	0.130	37.3	4.44
		15- x 15-in. Slab			
0	2.87	96	0.192	184.9	2.19
1	1.92	97	0.128	123.7	3.36
2	1.35	94	0.090	87.0	4.06
6	0.95	92	0.0635	61.3	4.55
		20- x 20-in. Slab			
0	2.72	92	0.136	311.9	2.21
1	1.79	98	0.090	205.5	3.38
3	0.92	95	0.046	105.3	4.46
6	0.80	94	0.040	91.7	4.62
		24- x 25-in. Slab			
1	1.77	85	0.072	304.5	3.34
		25- x 25-in. Slab			
6	0.71	83	0.028	127.1	4.67
		Infinite Slab (Extrapolated from above data)			
0	2.50 ± 0.15				2.25
1	1.6 ± 0.1				3.9
2	1.1 ± 0.1				4.5
6	0.60 ± 0.03				5.16

a. The accuracy of the critical thickness given in this column depends upon the precision of the neutron count rates, upon the extrapolation of the inverse multiplication curves and, for nominally unreflected slabs, upon extraneous neutron reflection by supports, etc. Of these, the uncertainty in the extrapolation, which probably controls the overall accuracy, may be estimated from the adjacent column, which lists the per cent of the extrapolated critical thickness which was assembled in each experiment, and from the extrapolated curves themselves in the Appendix. If Δt is the interval between the assembled thickness and the extrapolated thickness, the overall limits of uncertainty in the latter are estimated to be $-\Delta t/2$ and $+\Delta t$.

b. Based on an unreflected sphere extrapolation distance of 2.15 cm.

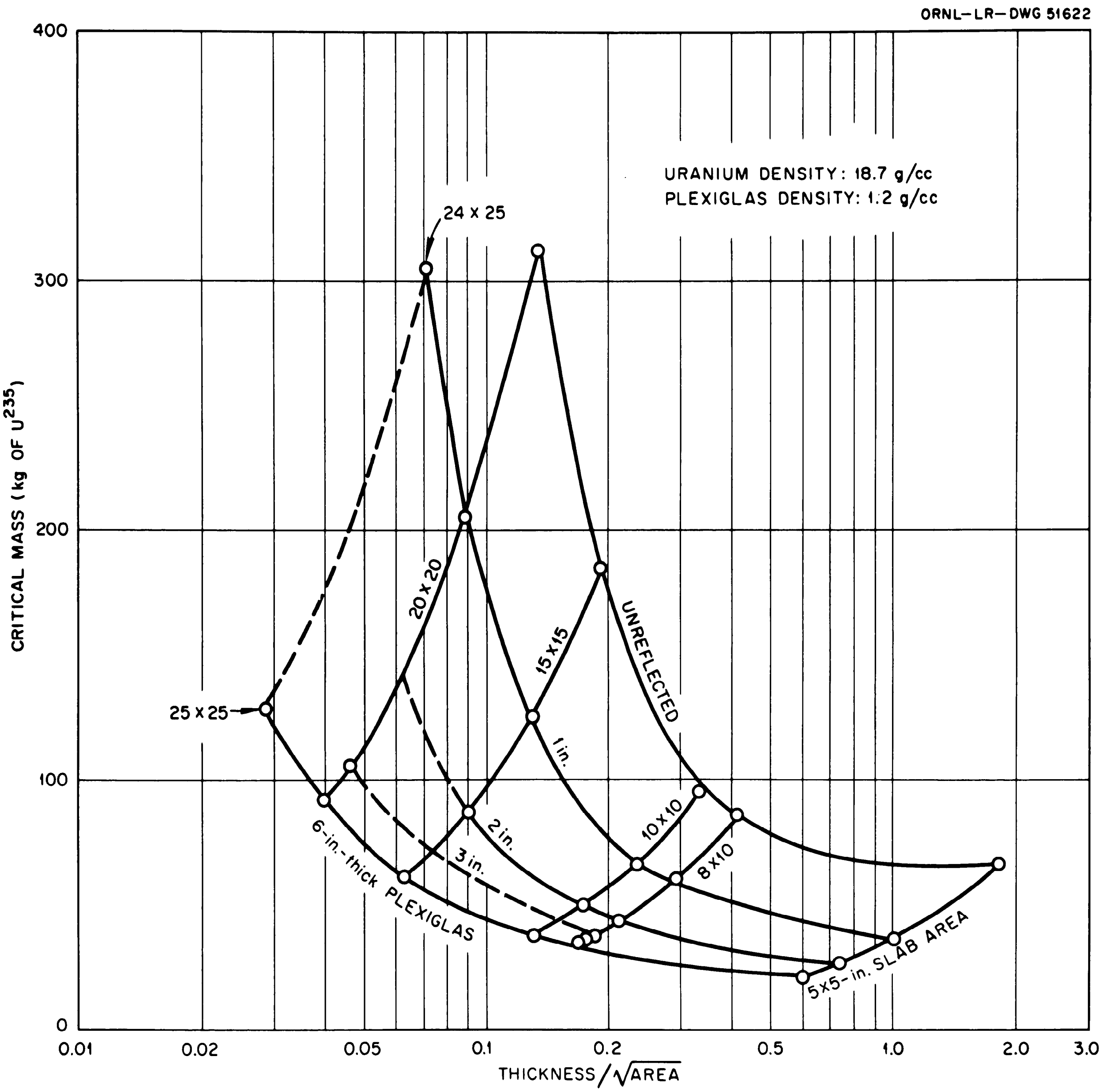

Fig. 3. Critical Mass of U^{235} as a Function of Parallepipedal Geometry for Bare and Plexiglas-Reflected Slabs.

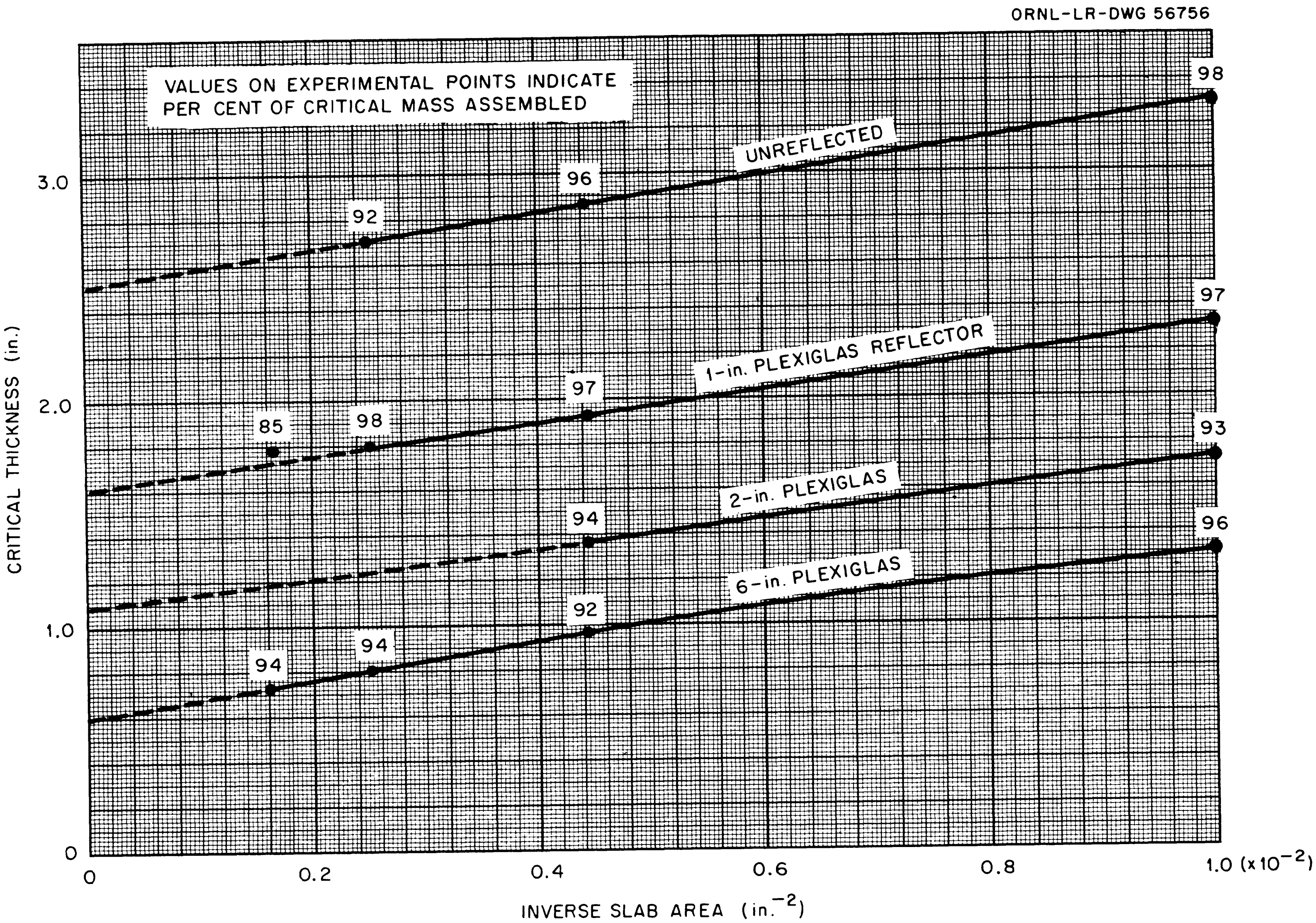

Fig. 4. Critical Thickness of 93.15% U^{235}-Enriched Uranium Slabs as a Function of Inverse Slab Area, for Various Reflector Conditions.

The effective extrapolation distance, λ_c, listed in Table 1 is that which satisfies the relation

$$B^2 = \left(\frac{\pi}{a + 2\lambda_c}\right)^2 + \left(\frac{\pi}{b + 2\lambda_c}\right)^2 + \left(\frac{\pi}{t + 2\lambda_c}\right)^2$$

for a parallelepiped with sides of lengths a and b and thickness t. The critical buckling, B^2, of the uranium was obtained from the dimensions of Godiva I, the unreflected critical sphere of 93.5% U^{235}-enriched uranium constructed at the Los Alamos Scientific Laboratory,[3] and an associated extrapolation distance of 2.15 cm. The effective extrapolation distance, plotted as a function of $tA^{-1/2}/(1 + tA^{-1/2})$, where A is the slab area, is shown in Fig. 5. The inadequacy of a conversion from one critical geometry to another by simply equating geometric bucklings embodying a constant extrapolation distance is emphasized by the dependence of the extrapolation distance on geometry shown in this graph. It is also evident that, the extrapolation distance becomes a strong function of the relative dimensions of the slab as the height-to-area ratio decreases.

The inverse source-neutron counting rates observed with slabs of various dimensions and Plexiglas reflector thicknesses are reported in Table A-2. The extrapolations of these data, upon which critical thicknesses are based, are shown in Figs. A-1 through A-6.

Data obtained from experiments employing AGOT graphite or beryllium as a neutron reflector are presented in Table 2 and Fig. 6. In experiments with graphite, the critical thickness of an 8 x 10 in. uranium slab was obtained for a series of reflector thicknesses ranging from 0 to 12 in. In the case of a beryllium reflector, the critical dimensions of a single slab, reflected with a 12-in.-thick beryllium slab, were 5.0 x 5.0 x 1.4 in. Counting data and extrapolations for these experiments are given in Tables A-3 and A-4 and in Figs. A-7 and A-8.

Tables A-5 and Fig. A-9 present the data and extrapolation from which a critical thickness of 2.5 in. was obtained for an 8 x 10 metal slab reflected on all sides, except for one of the 8 x 10 faces, by a 6-in.-thick layer of Plexiglas.

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3. R. E. Peterson and G. A. Newby, Nuclear Sci. and Engr. 1, 112 (1956).

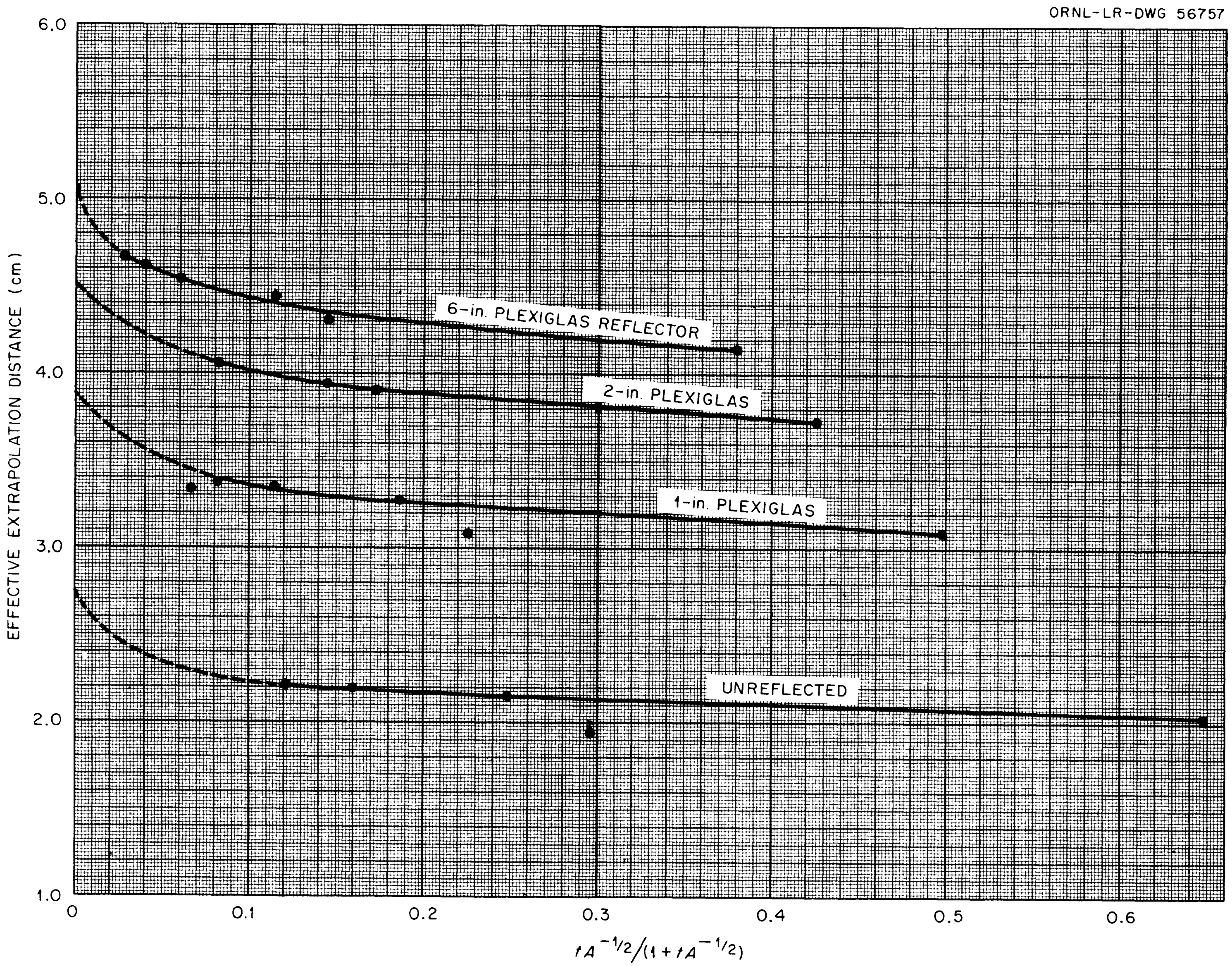

Fig. 5. Effective Extrapolation Distances for Parallelepipeds of 93.15 % U^{235} – Enriched Uranium Metal.

Table 2. Critical Thickness and Critical Mass of Slabs of 93.15%-U^{235}-Enriched Uranium Reflected with Various Thicknesses of Graphite and Beryllium

Reflector Thickness (in.)	Critical Thickness (in.)	Per Cent of Critical Thickness[a] Assembled	$\frac{h}{\sqrt{A}}$	Critical Mass (kg U^{235})	Effective Extrapolation Distance λ_c (cm)
		8- x 10-in. Slab, Graphite-Reflected			
1.43	2.52	94	0.28	57.7	3.22
2.87	2.11	95	0.24	48.4	3.67
5.75	1.65	91	0.18	37.8	4.18
12.0	1.32	95	0.15	30.3	4.55
		5- x 5-in. Slab, Beryllium-Reflected			
12.0	1.40	98	0.28	10.1	5.42

a. See footnote on Table 1.

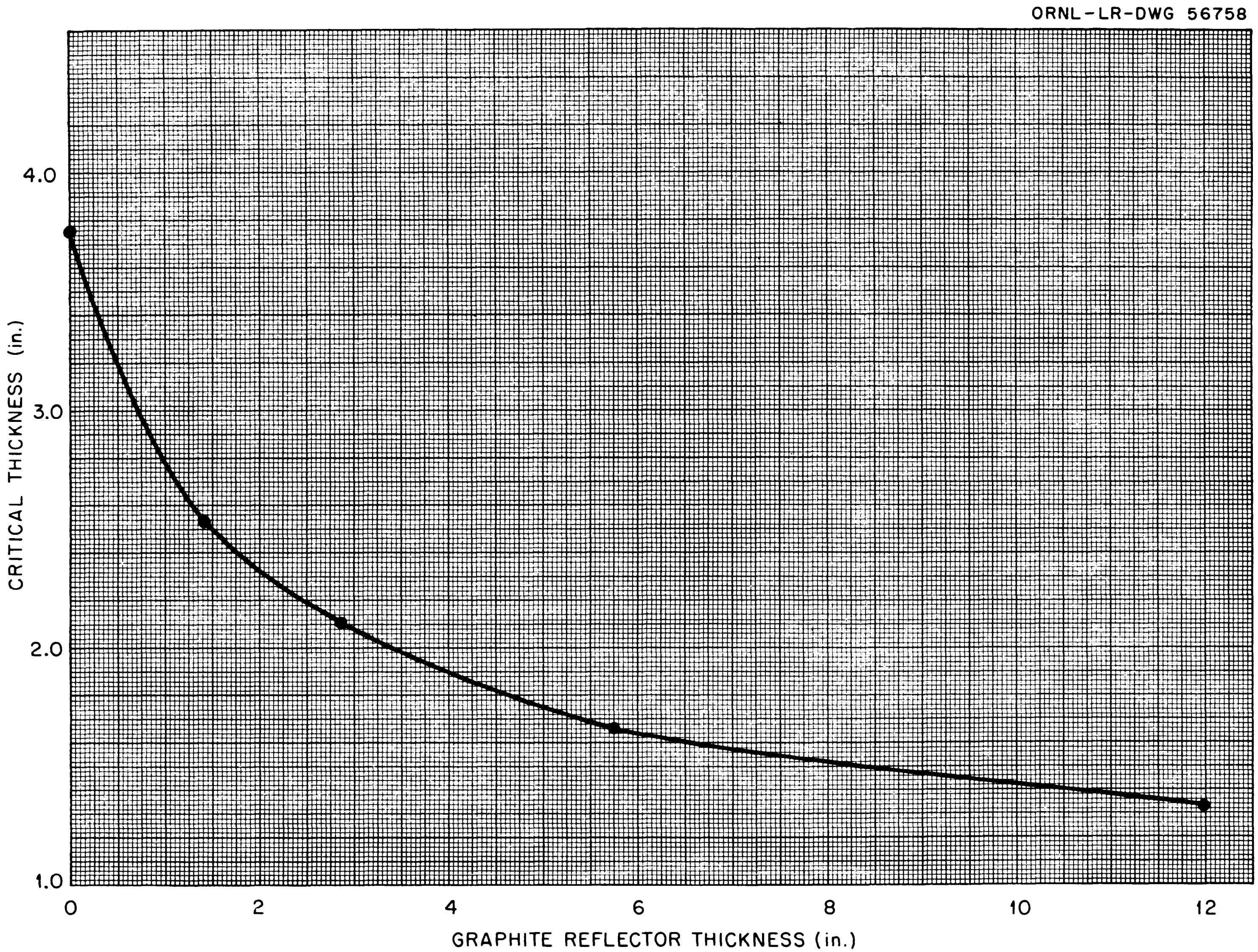

Fig. 6. Critical Uranium Thickness as a Function of Graphite Reflector Thickness for an 8-x 10-in. Slab of 93.15 % U^{235}– Enriched Uranium.

Lattice Experiments

Previous experiments[2] have established critical dimensions for 8- x 10-in. uranium slabs, 1-in. thick, arranged in lattices, with lattice densities ranging from 0.024 to 0.06. These measurements were extended in the present work to lattice densities of 0.33, at which point some void is still existent in the lattice cell, and 0.50, which represents the limit of contraction for an assembly of alternating 1-in.-thick uranium and 1-in.-thick Plexiglas slabs. A 1-in.-thick Plexiglas reflector surrounded both arrays.

The results have been combined with previously reported data as Fig. 7, with counting data plotted in Figs. A-10 and A-11.

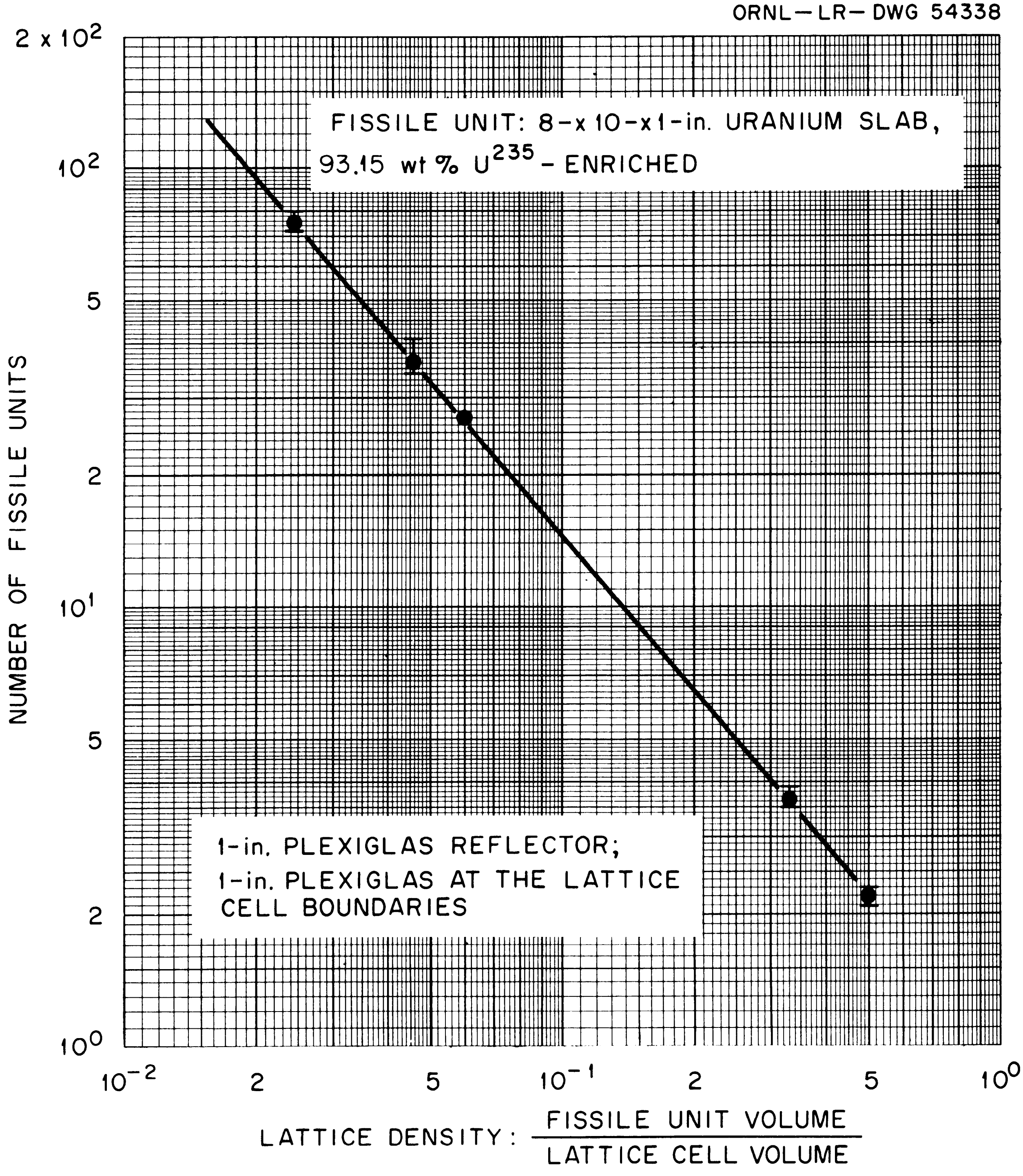

Fig. 7. Critical Number of 8-x 10-x 1-in. Slabs of 93.15 wt % U^{235}-Enriched Uranium Slabs as a Function of Ratio: Fissile Unit Volume Lattice Cell Volume.

Table A-1. Description of Machined Uranium Slabs Available for Experiment

Density: 18.7 g/cc

Isotopic Analysis (wt%)		Chemical Impurities (ppm)	
U^{234}	1.07	Al	10
U^{235}	93.15	C	400
U^{236}	0.68	Fe	40
U^{238}	5.10 (by difference)	Mo	50
		Si	40
		Others	trace

Details of Slabs

Length* (in.)	Width (in.)	Number Available			
		7/8-in. Thick	1/2-in. Thick	1/4-in. Thick	1/8-in. Thick
10	5	10**	2	2	10
10	3	4	2	2	4
10	2	4	2	2	4
5	5	4	4	4	4
5	2	4	4	4	4
5	1	2	2	2	2
1	1	4	-	-	4

* Tolerances: Dimensions, ± 0.002 in.; flatness, 0.002 in. total indicator reading.

** One with source hole.

Table A-2. Inverse Count Rate vs. Uranium Thickness for Slabs of 93.15% U^{235}-Enriched Uranium Reflected with Plexiglas

Uranium Thickness (in.)	Inverse Count Rate $(cpm)^{-1}$ No Reflector	1-in. Reflector	2-in. Reflector	3-in. Reflector	4-in. Reflector	6-in. Reflector	Uranium Thickness (in.)
			5- x 5-in. Slab				
	($x 10^{-4}$)	($x 10^{-4}$)	($x 10^{-4}$)	($x 10^{-4}$)	($x 10^{-4}$)	($x 10^{-4}$)	
0.87	1.78		3.07			6.68	0.87
1.00		1.86					1.00
1.75	1.68						1.75
2.00		1.67	1.84			4.09	2.00
2.62	1.48						2.62
2.75						1.44	2.75
3.00		1.67	0.65			0.22	3.00
3.25			0.43				3.25
3.50	1.39		0.20				3.50
3.62			0.95				3.62
4.00		1.09					4.00
4.37	1.10						4.37
4.50		0.53					4.50
4.75		0.25					4.75
5.37	0.81						5.37
6.37	0.47						6.37
6.87	0.38						6.87
7.37	0.27						7.37
7.87	0.19						7.87
8.37	0.11						8.37
8.87	0.03						8.87
			8 x 10 in. Slab				
0.87	1.15	1.42	1.11	1.07	1.40	2.76	0.87
1.00					1.11	2.18	1.00
1.12		1.12	0.78	0.66	0.76	1.53	1.12
1.25				0.45	0.54	1.03	1.25
1.37		0.87	0.50	0.29	0.28	0.56	1.37
1.50				0.16	0.09	0.10	1.50
1.62		0.62	0.25				1.62
1.75	0.72	0.55	0.13				1.75
2.00	0.56	0.35					2.00
2.25	0.44	0.20					2.25
2.50	0.34	0.073					2.50
2.62	0.30						2.62
2.87	0.22						2.87
3.12	0.15						3.12
3.37	0.084						3.37
3.50	0.056						3.50
3.62	0.023						3.62
			10 x 10 in. Slab				
0.87	1.22					2.16	0.87
1.00		0.85	0.67				1.00
1.12						0.88	1.12
1.25						0.30	1.25
1.50		0.49	0.19				1.50
1.62			0.083				1.62
1.75	0.70	0.32					1.75
2.00		1.98					2.00
2.65	0.31						2.65
2.87	0.20						2.87
3.12	0.089						3.12
3.25	0.040						3.25
			15 x 15 in. Slab				
0.50						3.52	0.50
0.62						2.60	0.62
0.75						1.67	0.75
0.87	1.23	0.97	0.69			0.64	0.87
1.00		0.84					1.00
1.12			0.29				1.12
1.25			0.12				1.25
1.50		0.48					1.50
1.62							1.62
1.75	0.67	0.17					1.75
1.87		0.059					1.87
2.00							2.00
2.25	0.39						2.25
2.50	0.25						2.50
2.75	0.088						2.75
			20 x 20 in. Slab				
0.50			1.04			2.66	0.50
0.62						1.56	0.62
0.75			0.39			0.45	0.75
0.87	1.24	0.95	0.10				0.87
1.12		0.69					1.12
1.37		0.42					1.37
1.62		0.17					1.62
1.75	0.65	0.04					1.75
2.25	0.35						2.25
2.50	0.17						2.50
			25 x 25 in. Slab				
0.25						4.38	0.25
0.50						2.05	0.50
0.59						1.21	0.59
			24 x 25 in. Slab				
1.25		4.20					1.25
1.37		3.14					1.37
1.50		2.20					1.50

Table A-3. Inverse Count Rate vs. Uranium Thickness for a 8- x 10-in. Slab of 93.15% U^{235}-Enriched Uranium Metal Reflected with Graphite

Uranium Thickness (in.)	Inverse Count Rate $(cpm)^{-1}$			
	1.43-in. Reflector	2.87-in. Reflector	5.75-in. Reflector	12-in. Reflector
	(x 10^{-4})	(x 10^{-4})	(x 10^{-4})	(x 10^{-4})
0.87			0.88	1.09
1.00	0.95	0.82		0.76
1.12			0.56	0.46
1.25		0.60		0.18
1.37			0.28	
1.50	0.57	0.40	0.15	
1.75	0.41	0.21		
1.87		0.13		
2.00	0.27	0.05		
2.25	0.14			
2.37	0.07			

Table A-4. Inverse Count Rate vs. Uranium Thickness for a 5- x 5-in. Slab of 93.15% U^{235}-Enriched Uranium Metal Reflected with 12 in. Beryllium

Uranium Thickness (in.)	Inverse Count Rate $(cpm)^{-1}$
	(x 10^{-4})
1.00	1.70
1.12	1.26
1.25	0.78
1.37	0.15

Table A-5. Inverse Count Rate vs. Uranium Thickness for a 8- x 10-in. Slab of 93.15% U^{235}-Enriched Uranium Metal Reflected with 6 in. Plexiglas on all but one 8- x 10-in. Face.

Uranium Thickness (in.)	Inverse Count Rate $(cpm)^{-1}$
	$(\times 10^{-4})$
1.50	1.07
1.75	0.75
2.00	0.47
3.25	0.26

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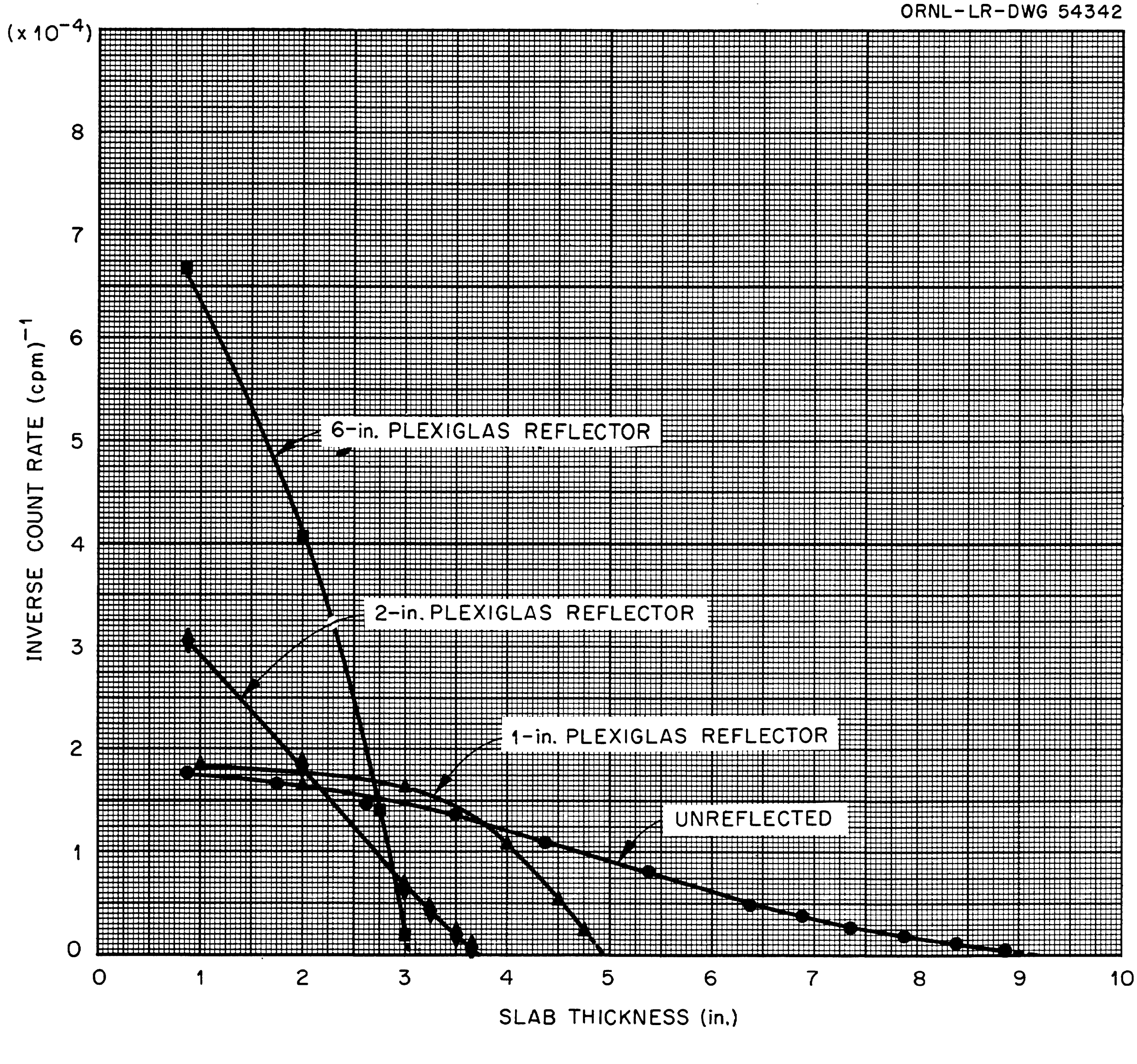


Fig. A-1. Inverse Count Rate as a Function of Slab Thickness for a 5- x 5-in., 93.15 wt % U^{235} – Enriched, Uranium Metal Slab.

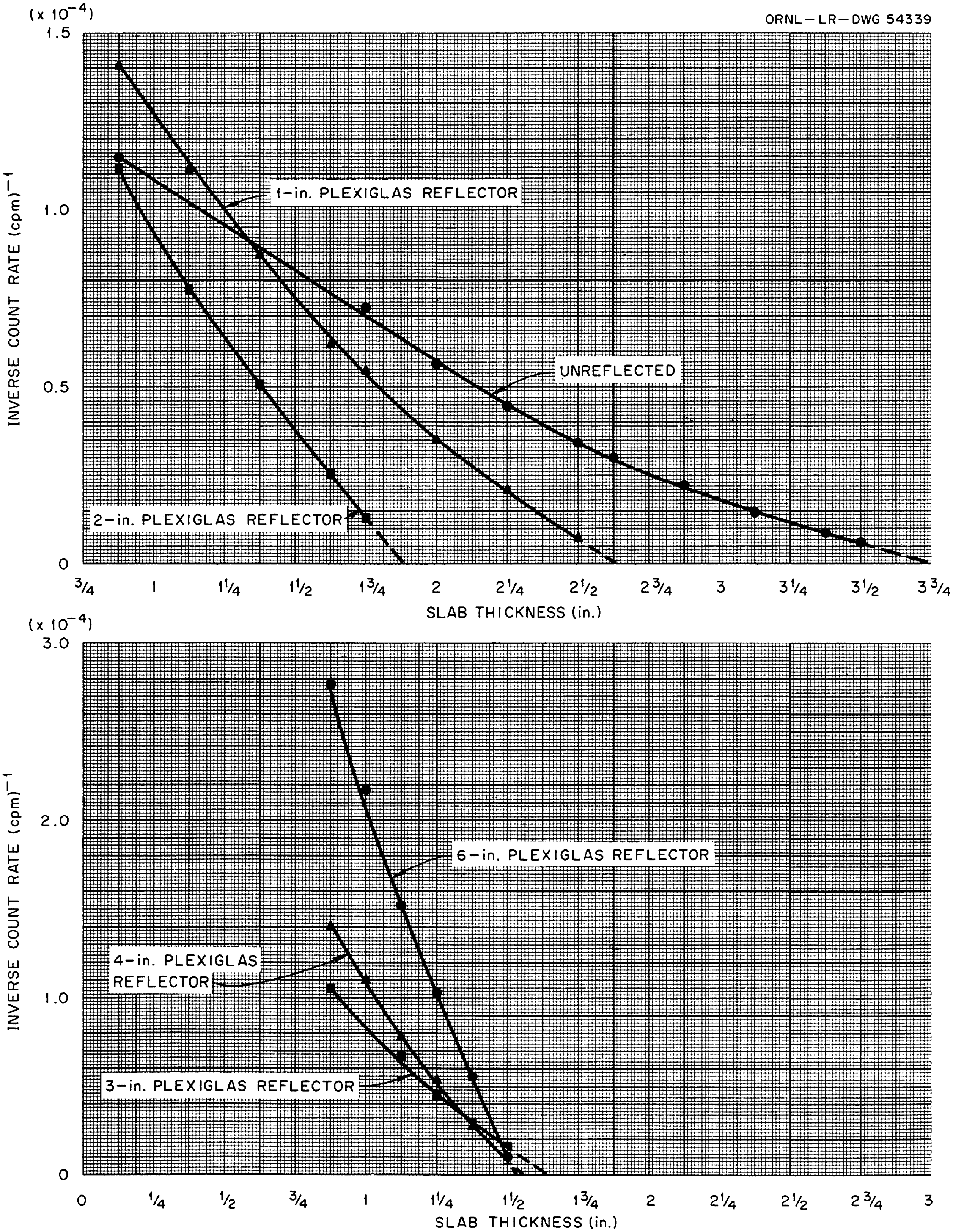


Fig. A-2. Inverse Count Rate as a Function of Slab Thickness for an 8-x 10-in., 93.15 wt % U^{235}-Enriched, Uranium Metal Slab.

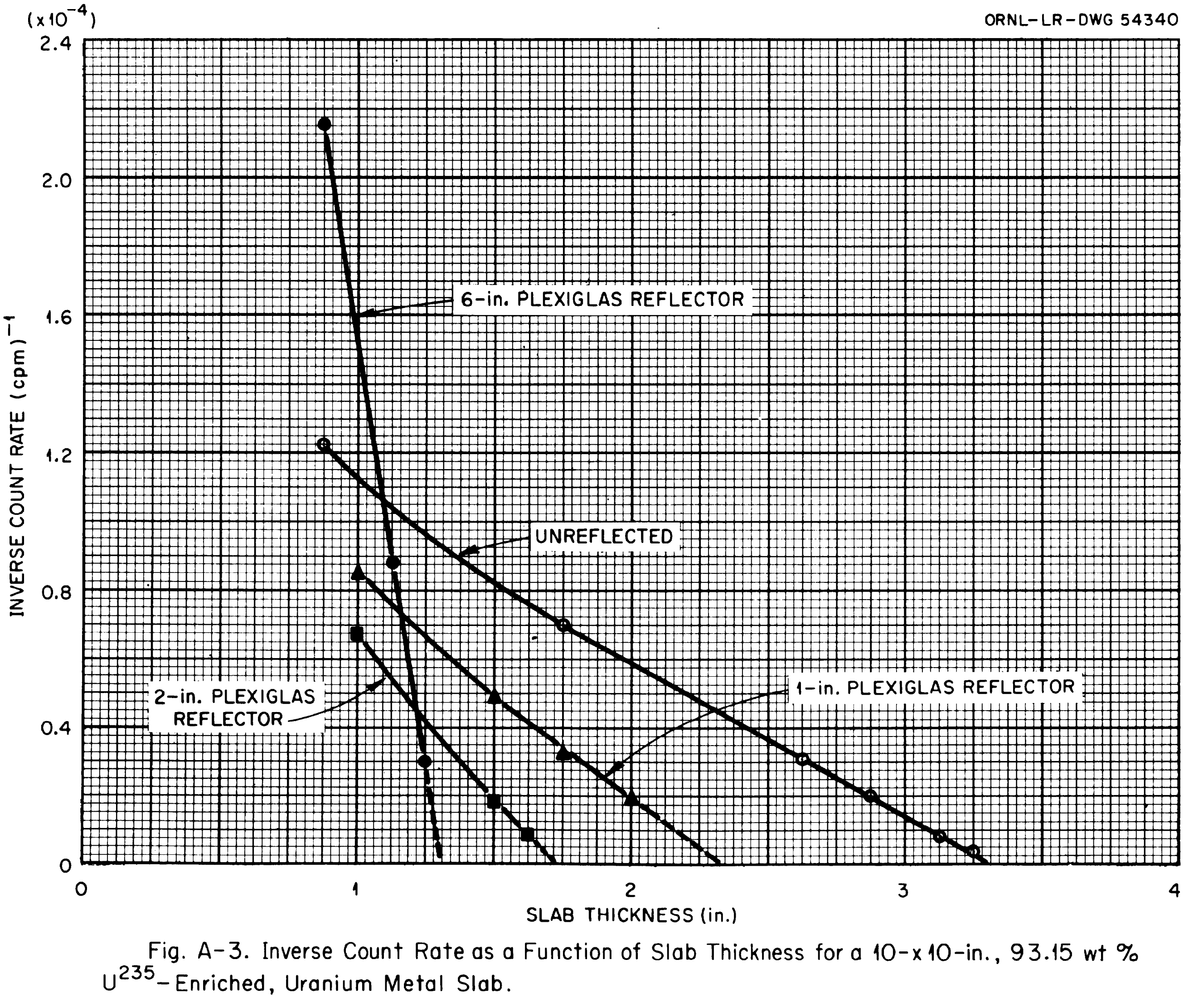


Fig. A-3. Inverse Count Rate as a Function of Slab Thickness for a 10-x10-in., 93.15 wt % U^{235}-Enriched, Uranium Metal Slab.

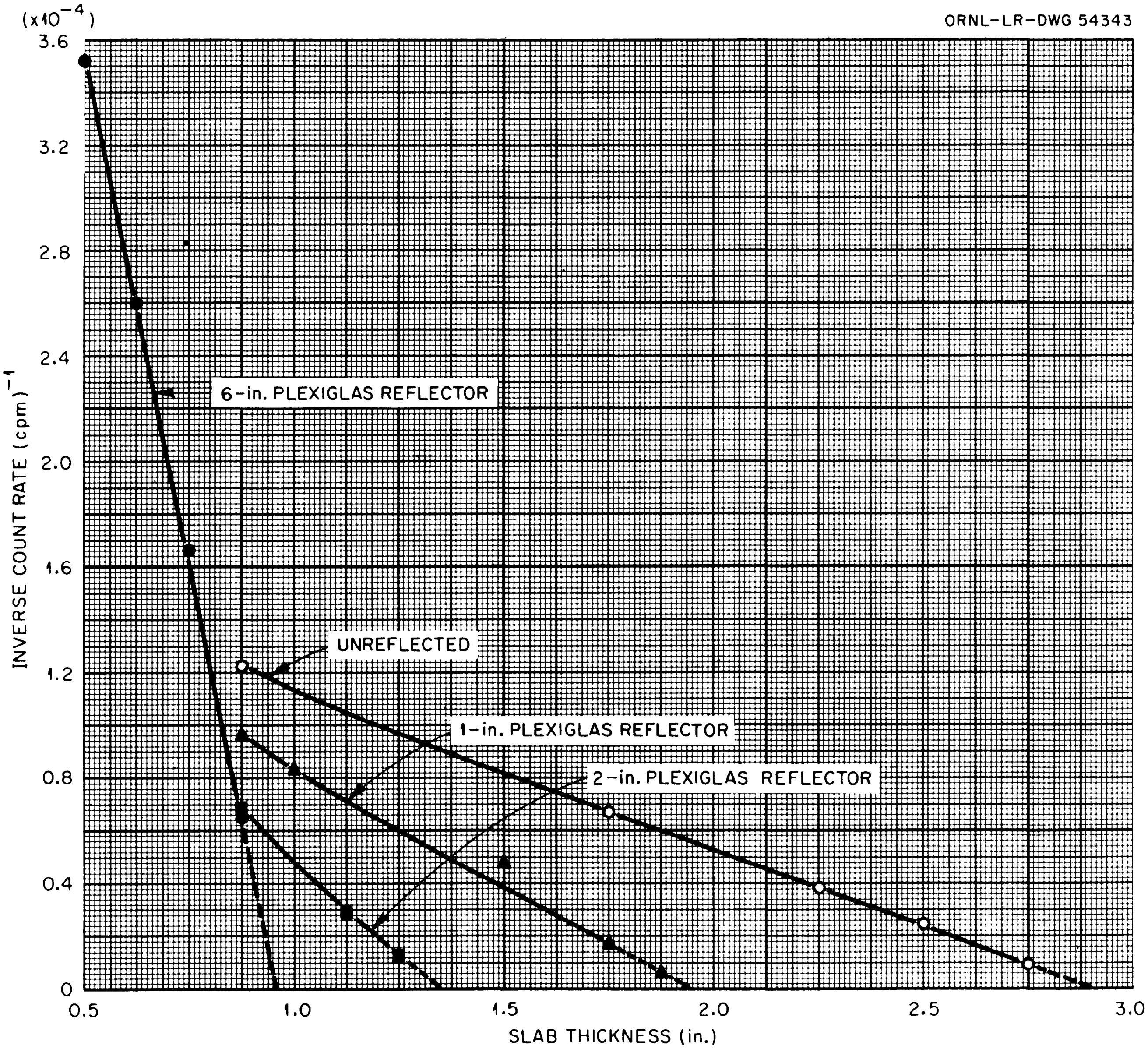


Fig. A-4. Inverse Count Rate as a Function of Slab Thickness for a 15-x 15-in., 93.15 wt % U^{235}-Enriched, Uranium Metal Slab.

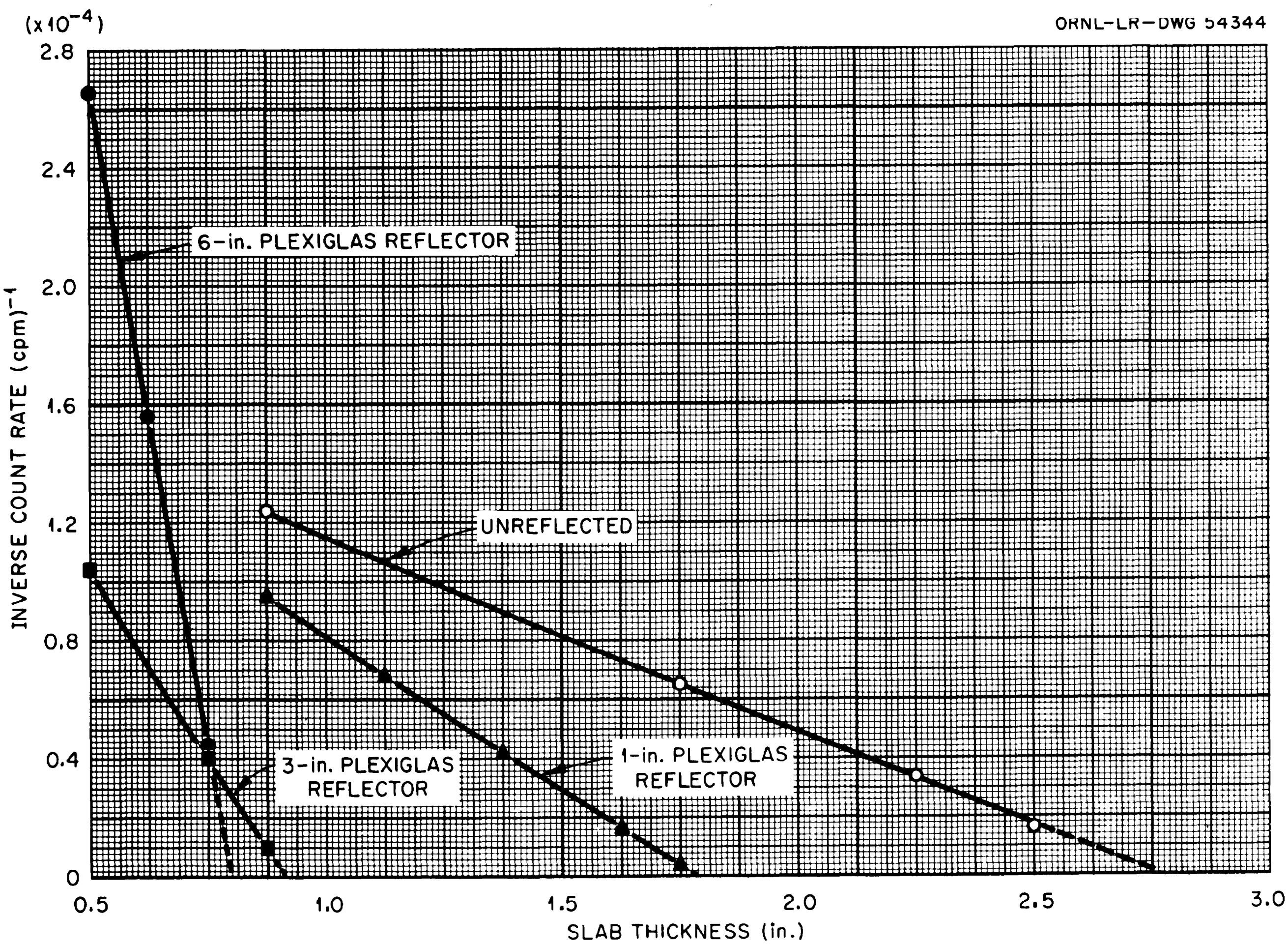
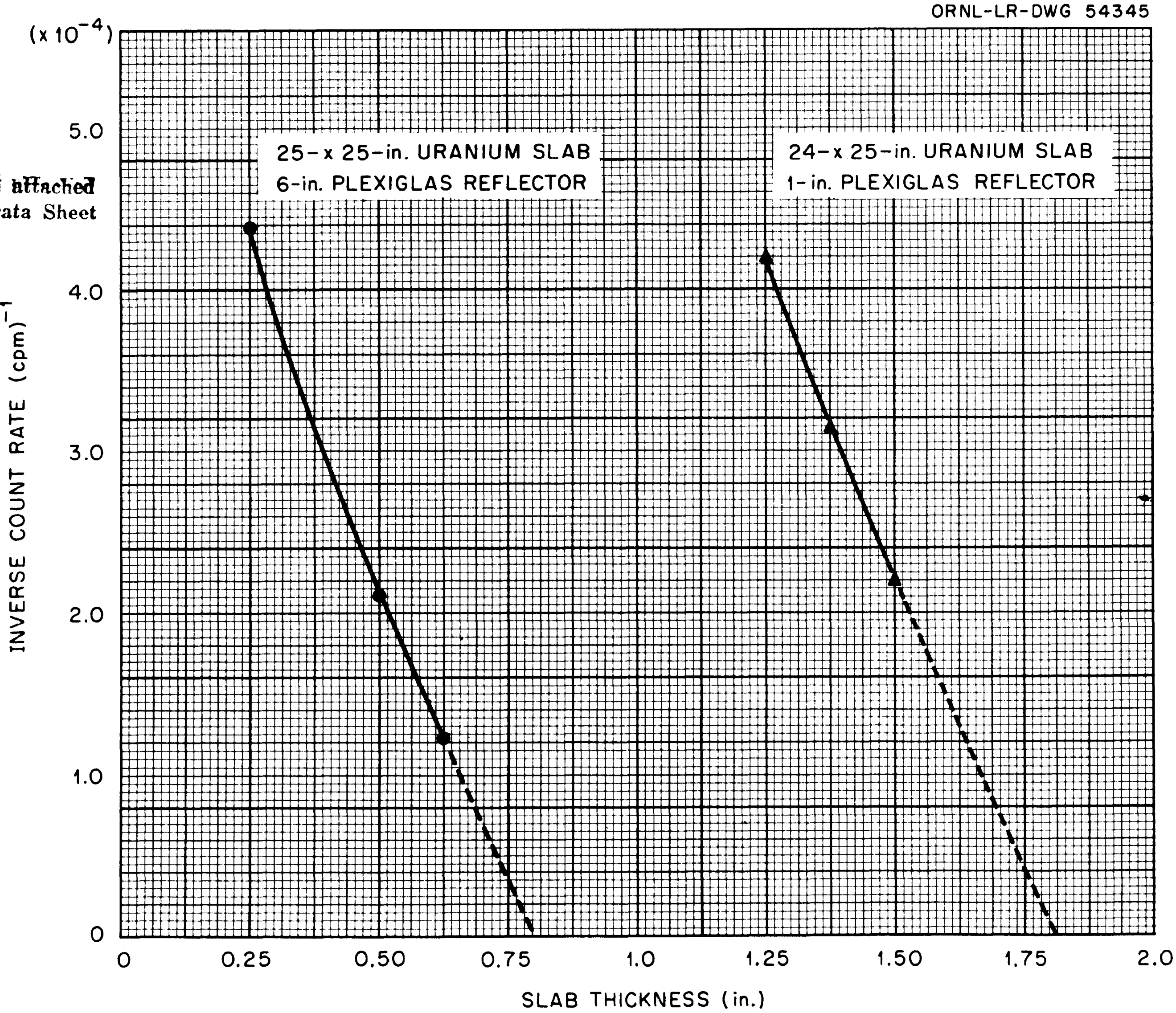


Fig. A-5. Inverse Count Rate as a Function of Slab Thickness for a 20- x 20-in., 93.15 wt % U^{235}-Enriched, Uranium Metal Slab.



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Errata Sheet

Fig. A-6. Inverse Count Rate as a Function of Slab Thickness for a 24-x 25-in. and a 25-x 25-in., 93.15 wt % U^{235}-Enriched, Uranium Metal Slab.

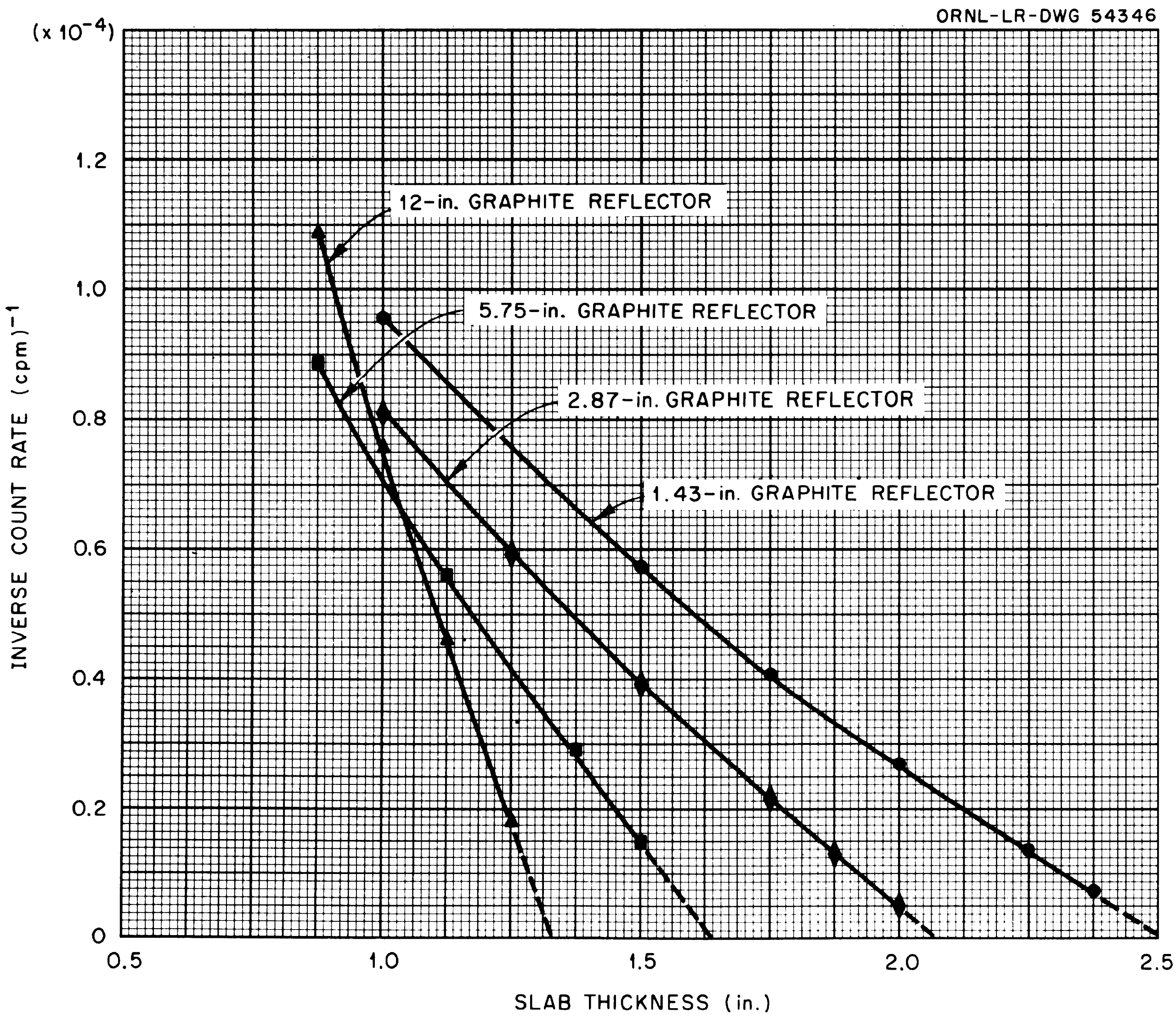

Fig. A-7. Inverse Count Rate as a Function of Slab Thickness for an 8-x 10-in., 93.15 wt % U^{235}-Enriched, Uranium Metal Slab.

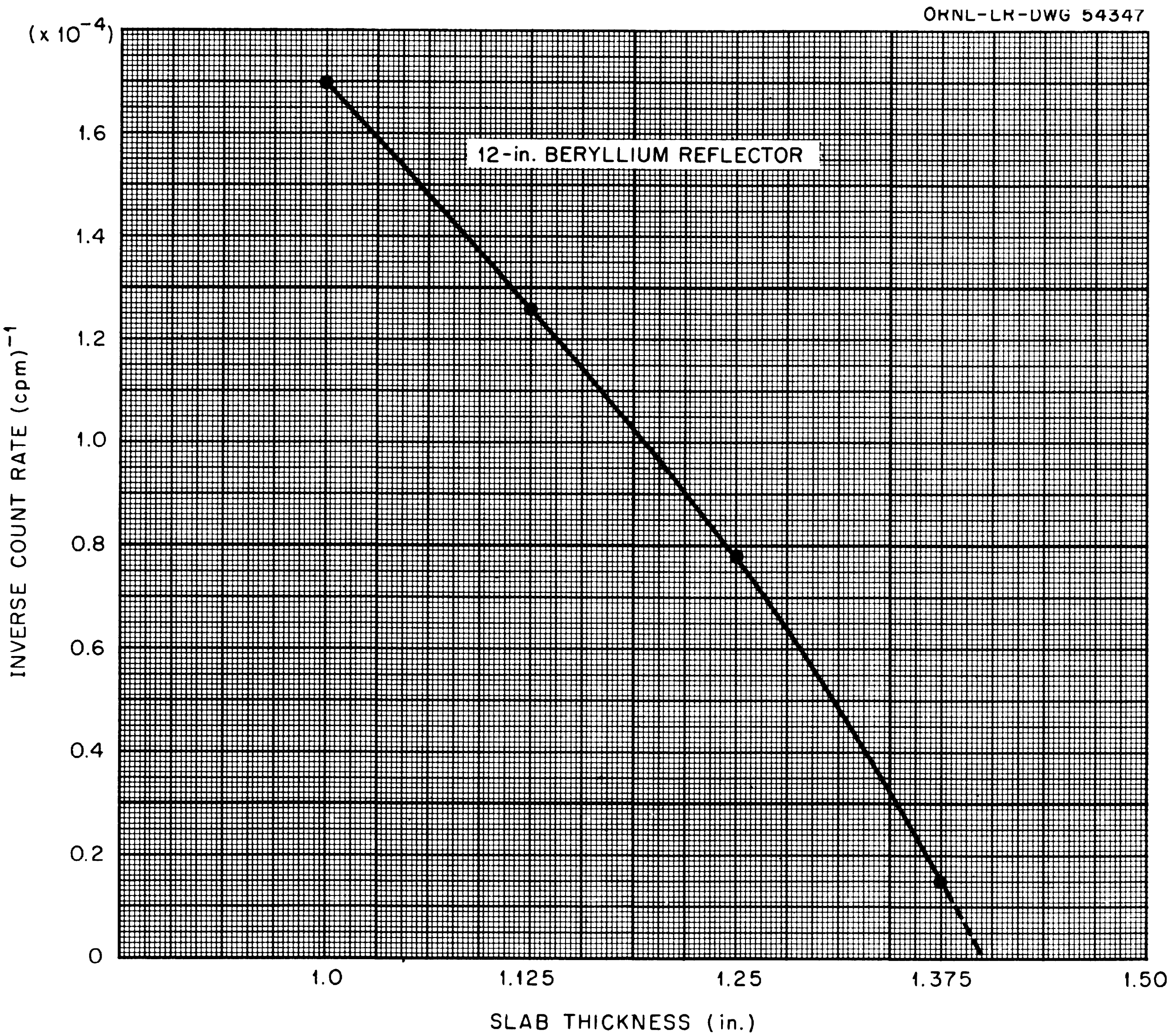

Fig. A-8. Inverse Count Rate as a Function of Slab Thickness for a 5- x 5-in., 93.15 wt % U^{235} - Enriched, Uranium Metal Slab.

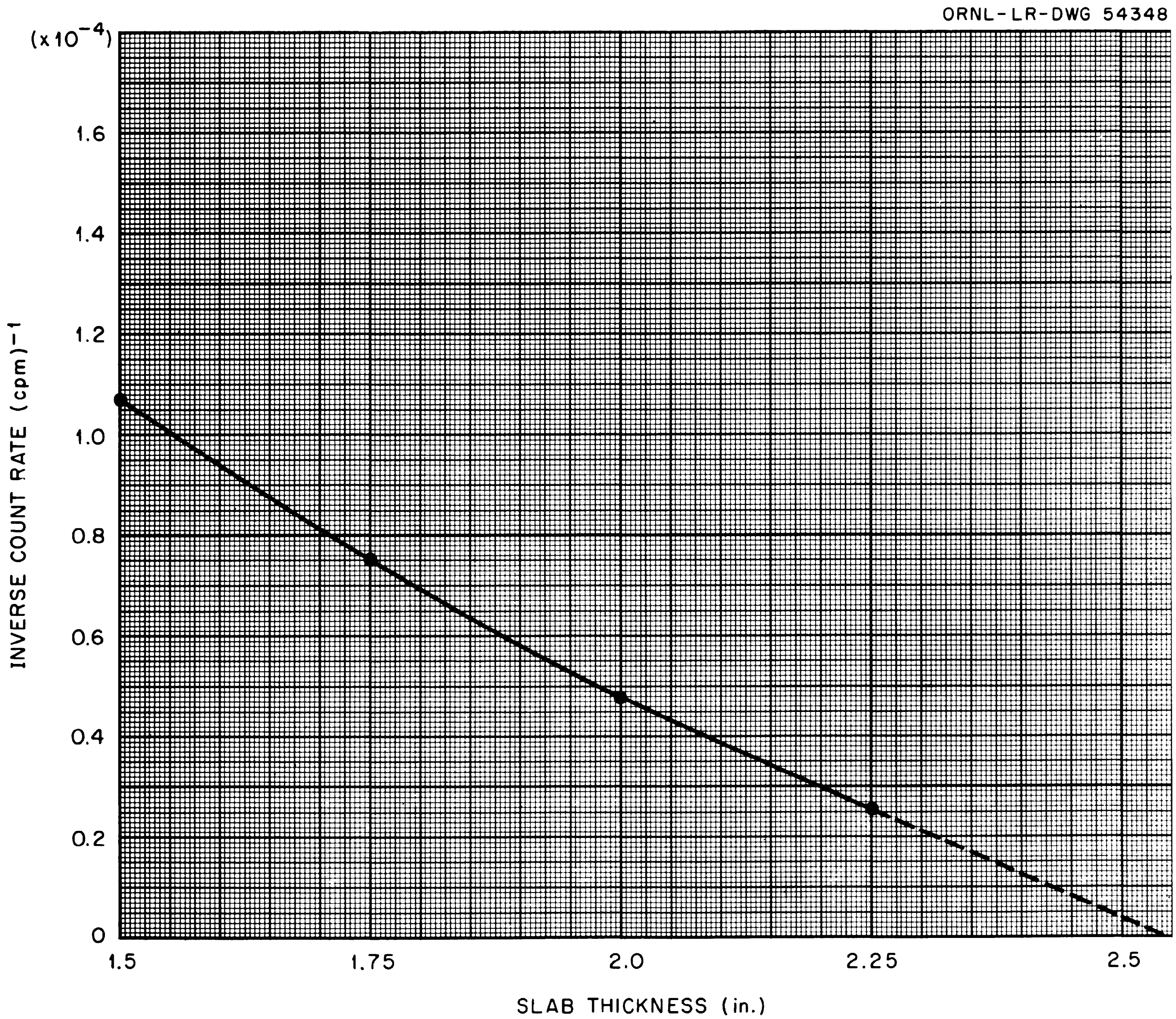

Fig. A-9. Inverse Count Rate as a Function of Slab Thickness for an 8-x 10-in., 93.15 wt % U^{235} - Enriched, Uranium Metal Slab. One of the 8-x 10-in. faces was unreflected; all other faces had 6 in. of Plexiglas reflector.

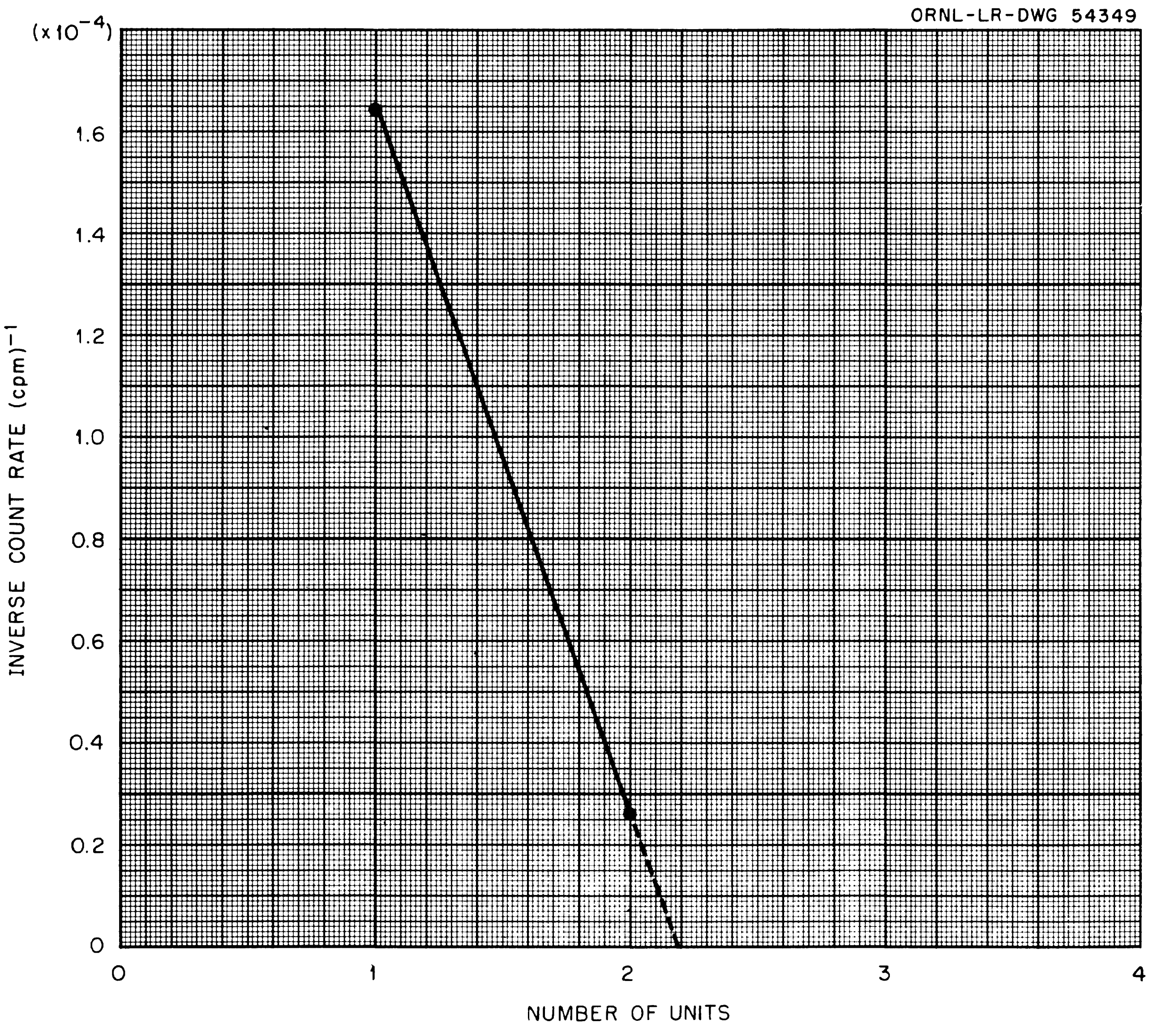

Fig. A-10. Inverse Count Rate as a Function of Number of Units for 8- x 10-in., 93.15 wt % U^{235} – Enriched, Uranium Metal Slabs Latticed with 1-in.-thick Plexiglas. Lattice Density = 0.5.

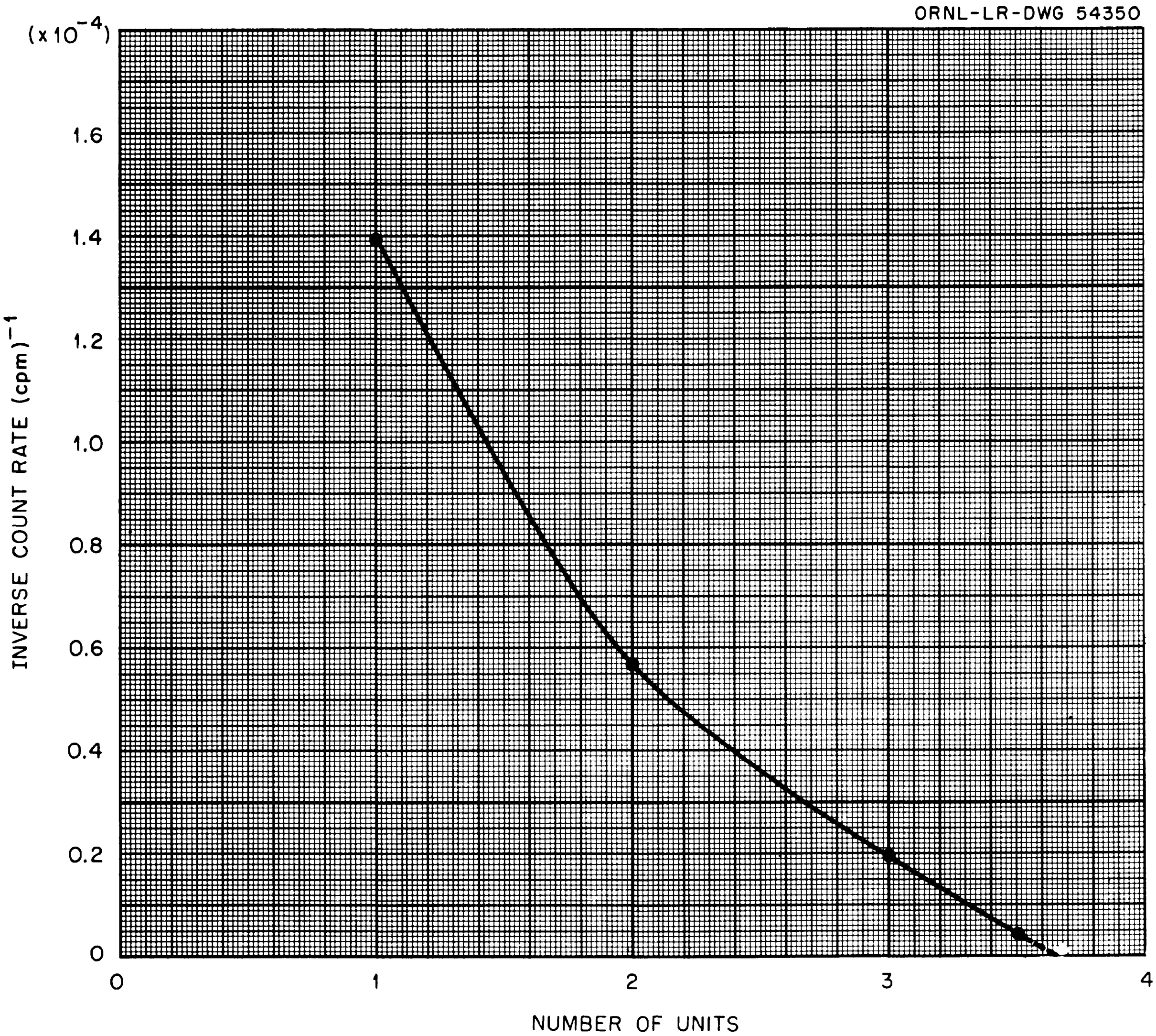

Fig. A-11. Inverse Count Rate as a Function of Number of Units for 8- x 10-in., 93.15 wt % U^{235}-Enriched, Uranium Metal Slabs Latticed with 1-in.-thick Plexiglas. Lattice density = 0.33 (½-in. Voids).

LIST OF FIGURES

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